Polarized emission from hot metals

R. More[(1)], M. Goto[(2)], P. Ni[(1)], H. Yoneda[(3)]
(1) Lawrence Berkeley National Laboratory, Berkeley, CA
(2) National Institute for Fusion Science, Toki, Gifu
(3) University of Electrocommunication, Chofu, Tokyo

HOW DO HOT METALS EMIT LIGHT?

Metal is an overdense plasma
Emission depends on dielectric function $\varepsilon(\omega) = \varepsilon_r + i\,\varepsilon_i$
For WDM made by ion heating, USP lasers or shock-release,
there can be a temperature gradient in the skin depth $\delta = c/\omega_p$
Thermal emission *is* strongly polarized
Polarization measurements may provide data to determine ε and T

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- o Transparent materials ==> radiative transfer theory
- o Expanding plasma with scale-length >> λ

  ==> emission from critical surface
- o Uniform temp ==> Kirchhoff law ==> absorption theory

  Emission = $E(\omega)\, B(\omega, T)$ $\qquad$ $E(\omega) = A(\omega)$

In these cases thermal emission is easily understood, but

Radiative transfer fails for sharp interfaces and overdense material
Early-time expansion has scale length << δ << λ
Kirchhoff's law is not valid when the T is not uniform

We need a more powerful theory of emission of light

Maxwell Equations

$$\nabla \times E = -\frac{1}{c}\frac{\partial B}{\partial t} \qquad \nabla \times B = \frac{4\pi}{c}J + \frac{1}{c}\frac{\partial E}{\partial t}$$

$$\nabla \cdot E = 4\pi\rho \qquad \nabla \cdot B = 0$$

vector identities: $a \times (b \times c) = (a \cdot c)\, b - (a \cdot b)\, c$

$div\,(a \times b) = b \cdot curl\, a - a \cdot curl\, b$

Energy theorem:

$$U_{EM} = \frac{1}{8\pi}\left(E^2 + B^2\right) \qquad S_{EM} = \frac{c}{4\pi}(E \times B)$$

$$\frac{\partial U_{EM}}{\partial t} + \nabla \cdot S_{EM} = -J \cdot E = -\sigma E^2$$

With $J = \sigma E$ (Ohm's law), only Joule heating = absorption

Slightly shocking that this "exact" textbook calculation omits half of the physics.

Search for a clean fundamental theory:

solid, liquid, WDM ---- > $\varepsilon(\omega)$ ---- > Emissivity $E(\omega)$

Relevant basic physics:

Emission "source function" is determined by the AC conductivity $\sigma(\omega)$

$$\varepsilon(\omega) = 1 + \frac{4\pi i\sigma(\omega)}{\omega}$$

Kubo formula and Weiner-Kinchin theorem
Green's functions for **E, B** fields
Coherence and fluctuations < ------ QED
Detailed balance (Kirchhoff law)

Detailed balance gives a reliable test for the case $T(\mathbf{r}) = \text{const}$

Emission theory - general case

Add emission from incoherent sources because
the Poynting vector $\mathbf{S} = c(\mathbf{E}\mathrm{X}\mathbf{B})/4\pi$ is quadratic

$$\mathbf{E} = G_E \circ \mathbf{j} \qquad \text{and} \qquad \mathbf{B} = G_B \circ \mathbf{j}$$

$$S \approx \frac{c}{4\pi} \int G_E \times G_B \circ \left\langle \; j \circ j \; \right\rangle dx$$

$< \mathbf{j} \circ \mathbf{j} >$ ==> autocorrelation ==> $\mathrm{Re}[\,\sigma\,] \sim \mathrm{Im}\,[\,\varepsilon\,]$

Kubo relation + Wiener-Kinchin theorem
Emission eq. includes coherent absorption process
Overdense radiation heat conduction

G's are matrix products

Detailed Balance: Emission = Absorption from BB spectrum

The theory has limitations:

Metal $\omega < \omega_p$ i.e., $\mathrm{Re}[\,\varepsilon\,] < 0$	Not insulator, rock, glass, salt
Sharp and smooth surface	*For now, planar geometry*
Linear electrodynamics $J = \sigma E$	No superconductivity; No nonlinear optical processes
Isotropic local $\sigma(\omega)$	No anisotropic single crystals No anomalous skin effect
Not X-rays or EUV at $\omega > \omega_p$	

Emission during shock release

Questions:

What's the time-profile of the light flash after shock release?

Does that emission determine the bulk shock temperature?

Calculation uses a Drude-model dielectric function for aluminum to calculate emission from shock-release based on a new EOS.

EOS is realistic, but not $\varepsilon(\omega, \rho, T)$, so the calculation should be done with better ε.
Plan to integrate the emission calculation with a hydrocode and perform *many* calculations to match experimental data.

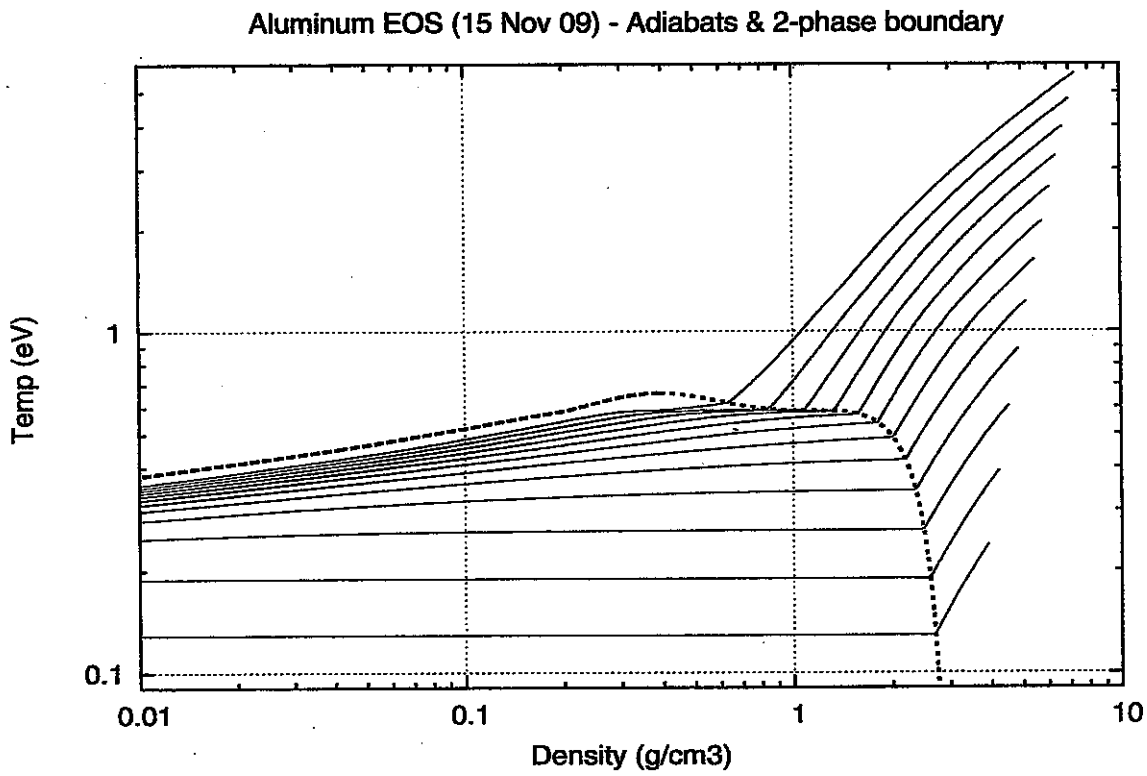
Question about *time resolution* that can be achieved in experiments.

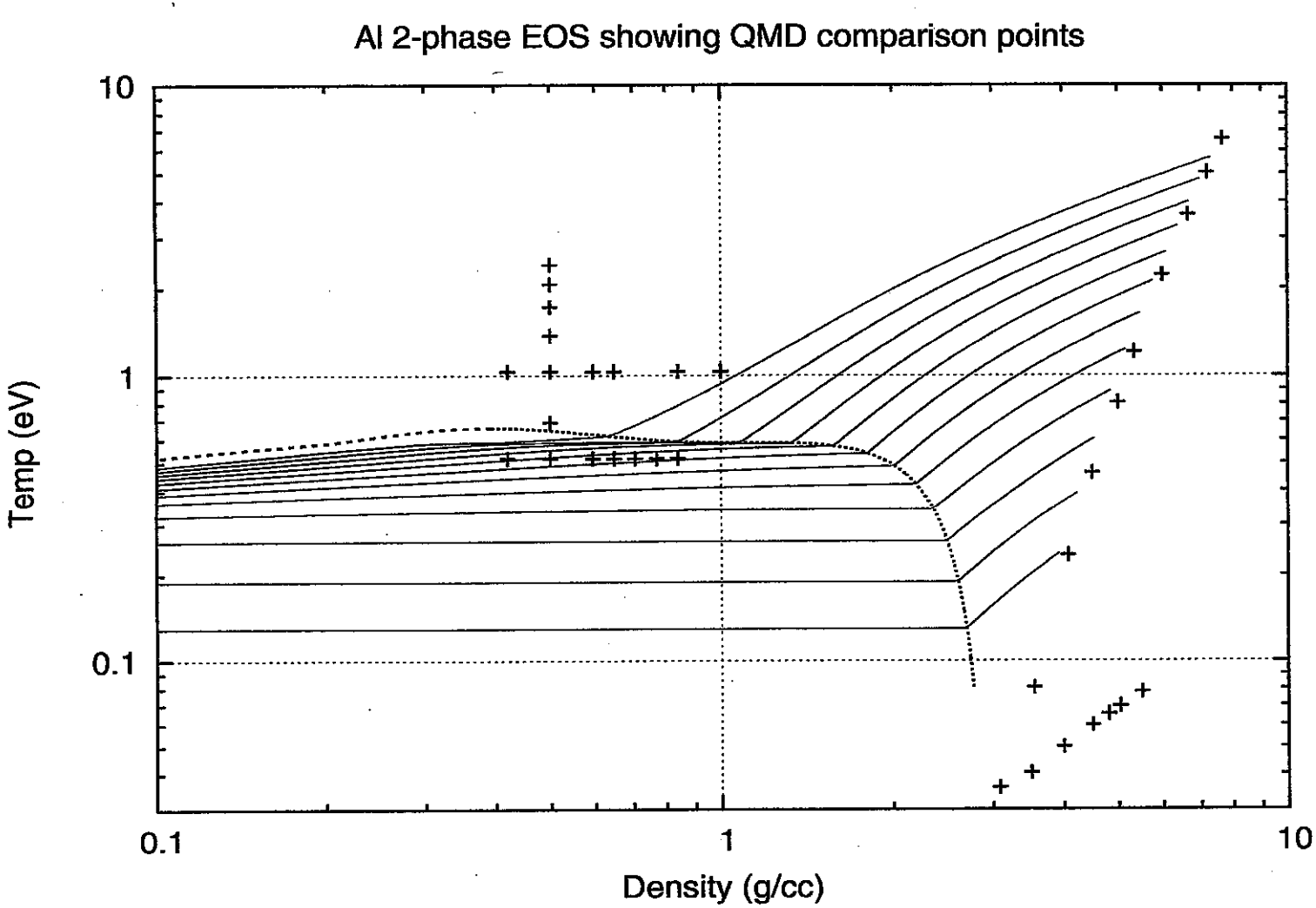
Simultaneous observation with several angles, polarizations and wavelengths would strongly constrain models for shock temperature, $\varepsilon(\omega)$ and EOS.

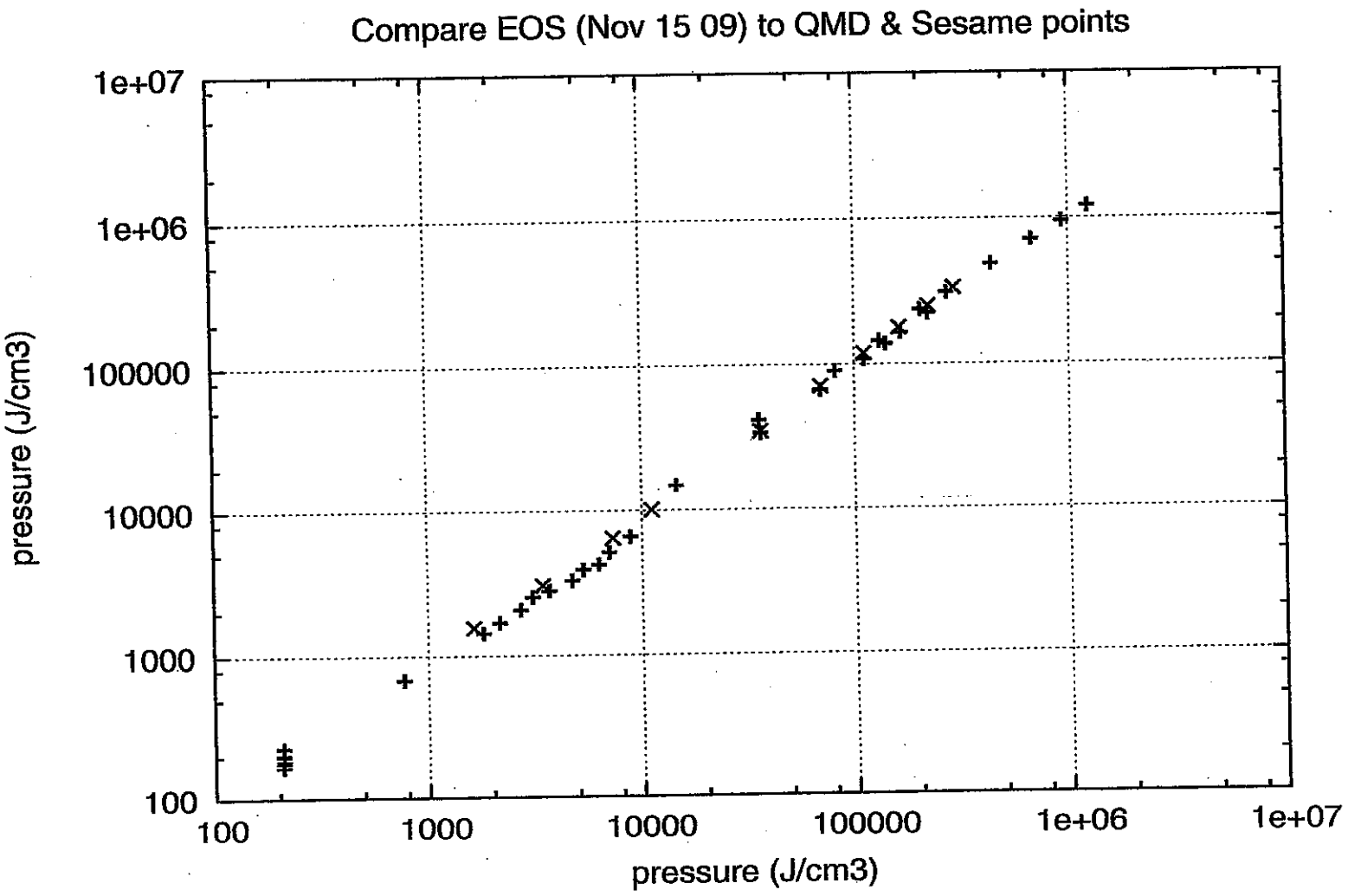
NEW EOS for Aluminum includes Al_2 dimer

RMM

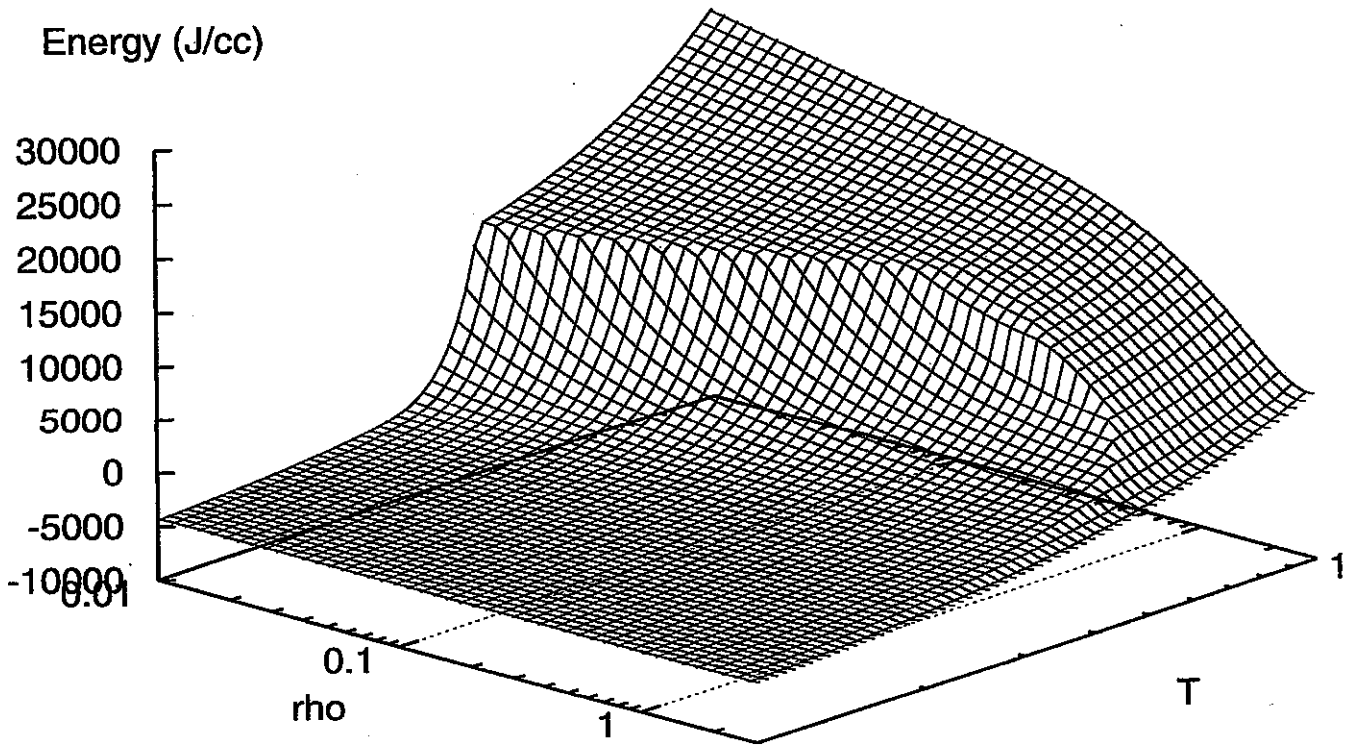
Includes Gruneisen, Debye, fluid-scaling, TF, bonding & 2-phase Maxwell construction like QEOS
also includes aluminum dimer (**Al_2**) with binding energy ~ **1.38 eV**
Dimers are destroyed by high pressure, replaced by metallic (solid/liquid) bonding
This leads to a surprising liquid-liquid phase transition, like a second critical point
EOS was adjusted to approximately match 26 QMD calculations by M. P. Desjarlais (SNLA)
This is theory + theory and needs experimental testing

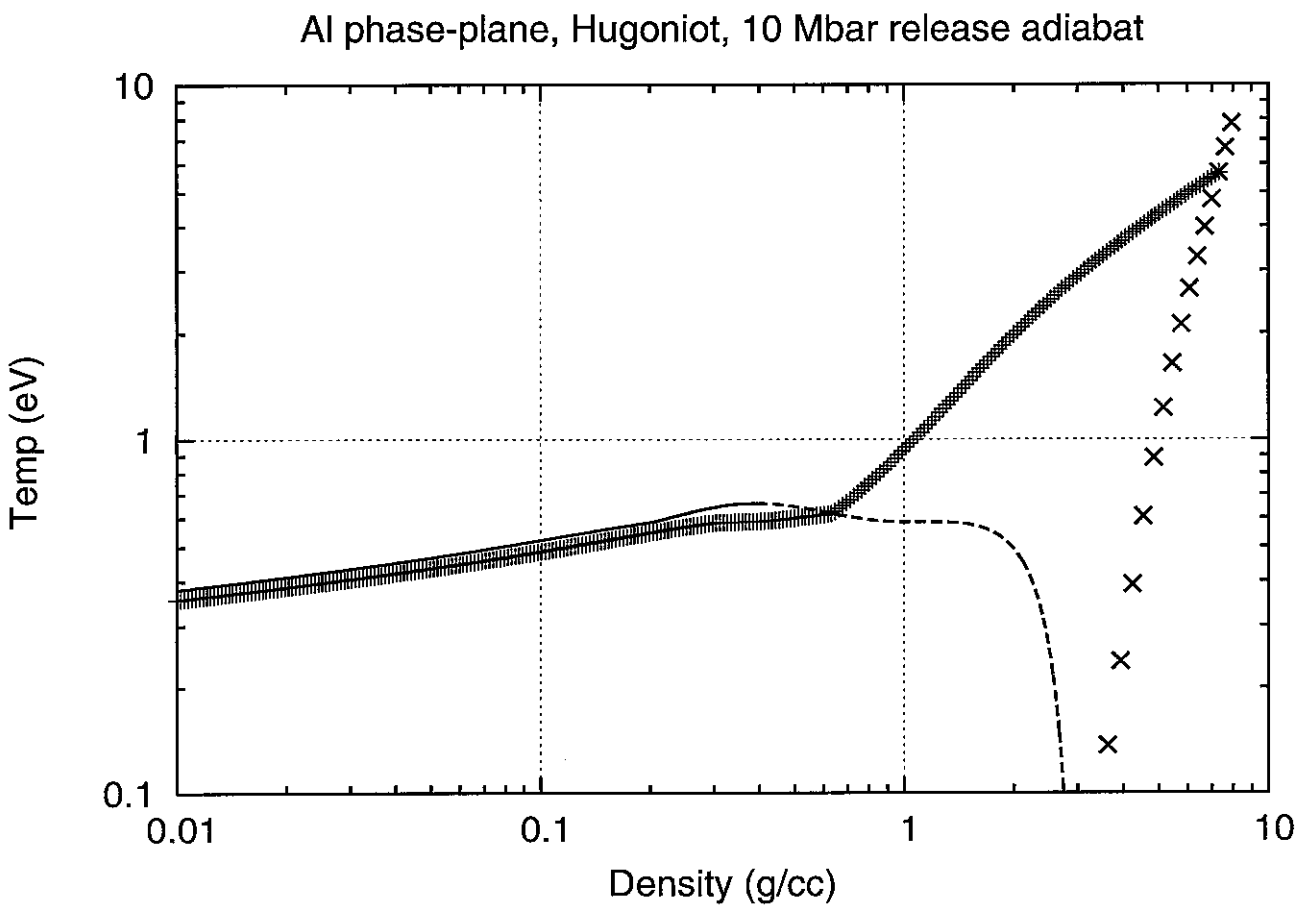


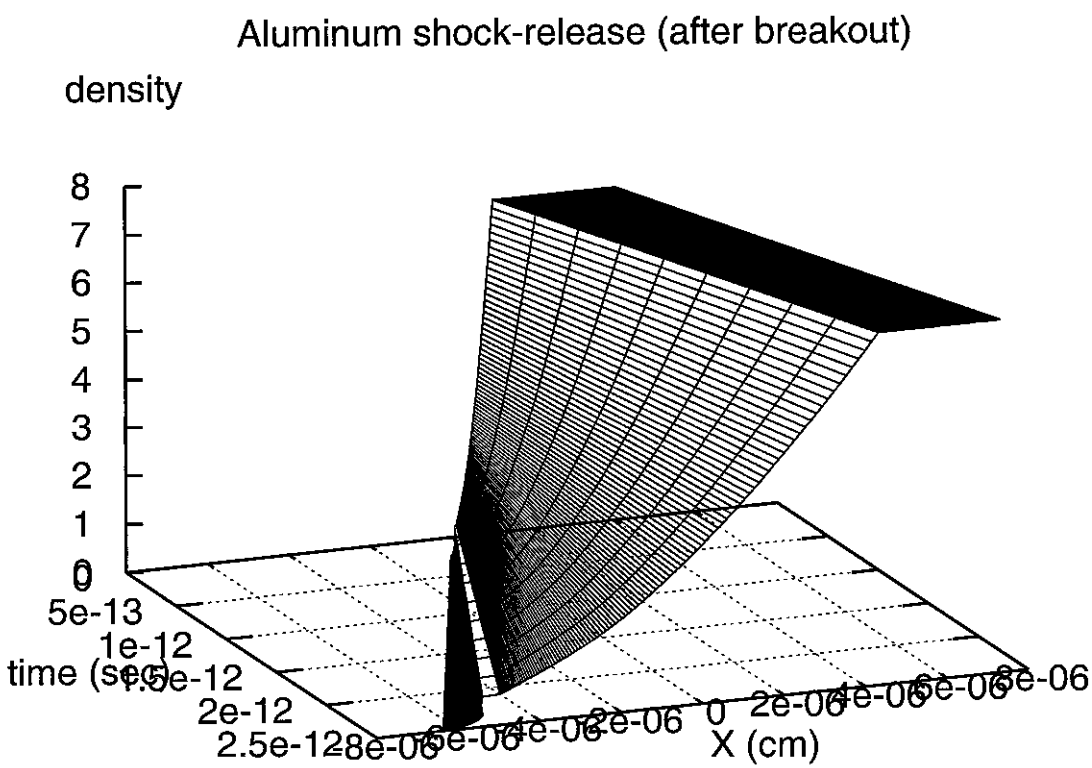

Al 2-phase EOS showing QMD comparison points
10
1
0.1
Temp (eV)
0.1
1
10
Density (g/cc)


Compare EOS (Nov 15 09) to QMD & Sesame points
1e+07
1e+06
100000
10000
1000
100
pressure (J/cm3)
100
1000
10000
100000
1e+06
1e+07
pressure (J/cm3)

Energy surface of Al EOS near 2 cp condition




Al phase-plane, Hugoniot, 10 Mbar release adiabat
10
1
0.1
Temp (eV)
0.01
0.1
1
10
Density (g/cc)


Aluminum shock-release (after breakout)
density
8
7
6
5
4
3
2
1
0
0
5e-13
1e-12
1.5e-12
2e-12
2.5e-12
time (sec)
-8e-06
-6e-06
-4e-06
-2e-06
0
2e-06
4e-06
6e-06
8e-06
X (cm)

Aluminum shock-breakout emission calculation

EOS = dimer EOS fit to QMD calculations from M. Desjarlais

Described in APS Plasma meeting in Dallas (2008) and Santa Barbara RPHDM

$p_{sh} = 10.3$ Mbar $\rho_{sh} = 7.31$ g/cc $T_{sh} = 5.65$ eV

Dielectric function from Drude theory with

TF ionization $Z^*(\rho, T)$ plasma frequency $\omega_p = 4\pi Z^* n_i e^2 / m_e$

AC conductivity $\sigma(\omega) = n_e e^2 \tau / m_e(1 - i\omega\tau)$

Dielectric function $\varepsilon(\omega) = 1 + 4\pi i \sigma(\omega) / \omega$

Observe:

Emission flash lasts longer for long wavelengths

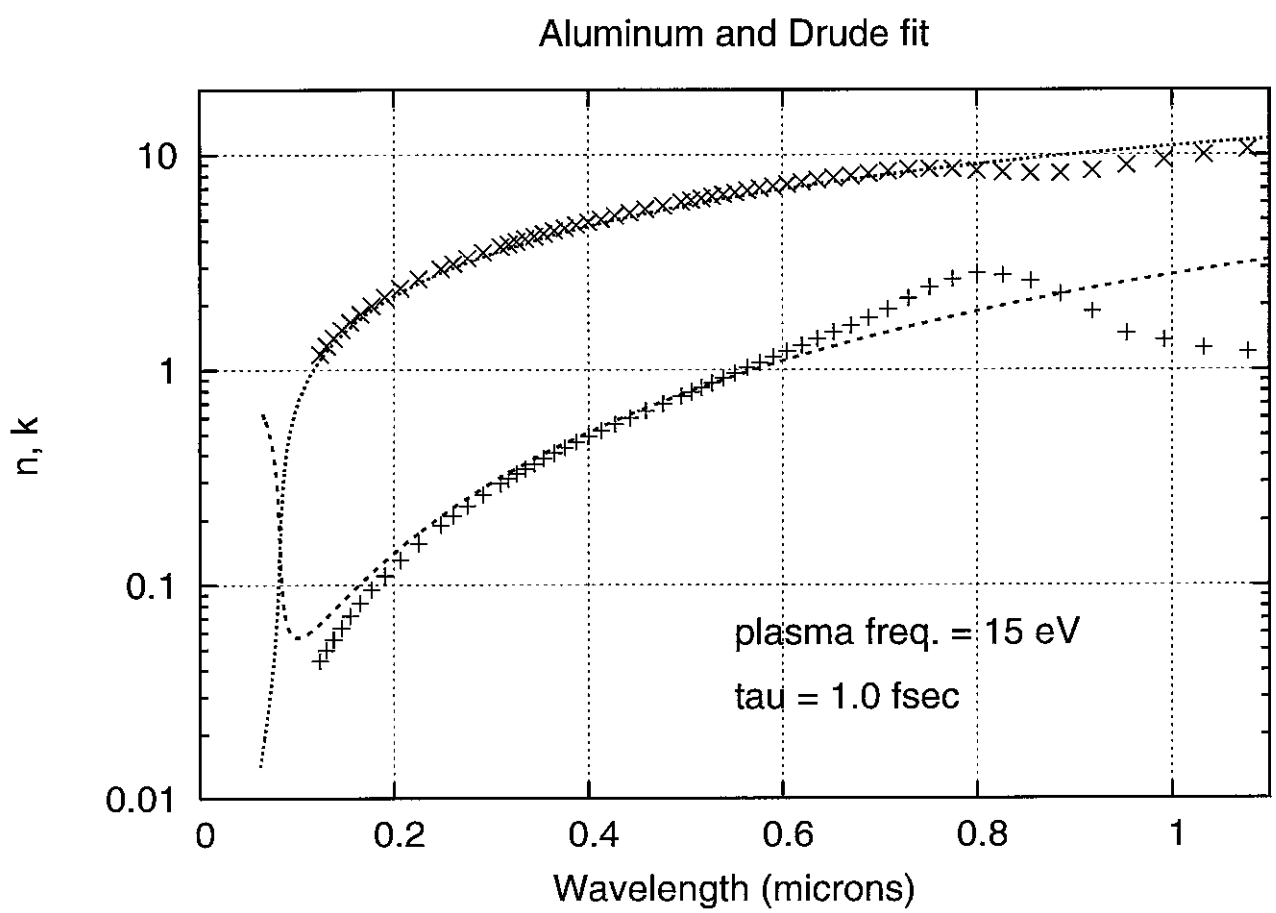
Time duration $\geq$ 1 psec

Strong polarization $p >> s$

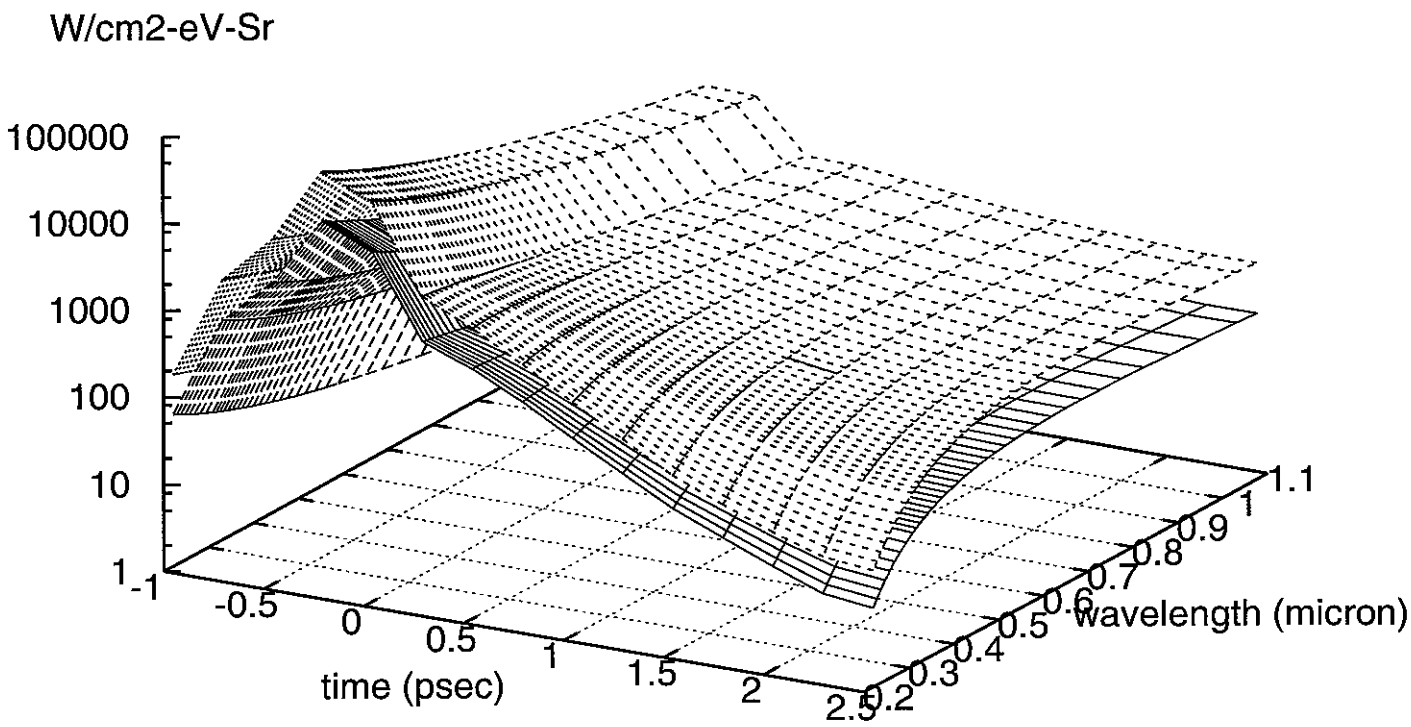
Emissivity defined wrt bulk (shock) temperature decreases rapidly

Slight increase of absorption coefficient

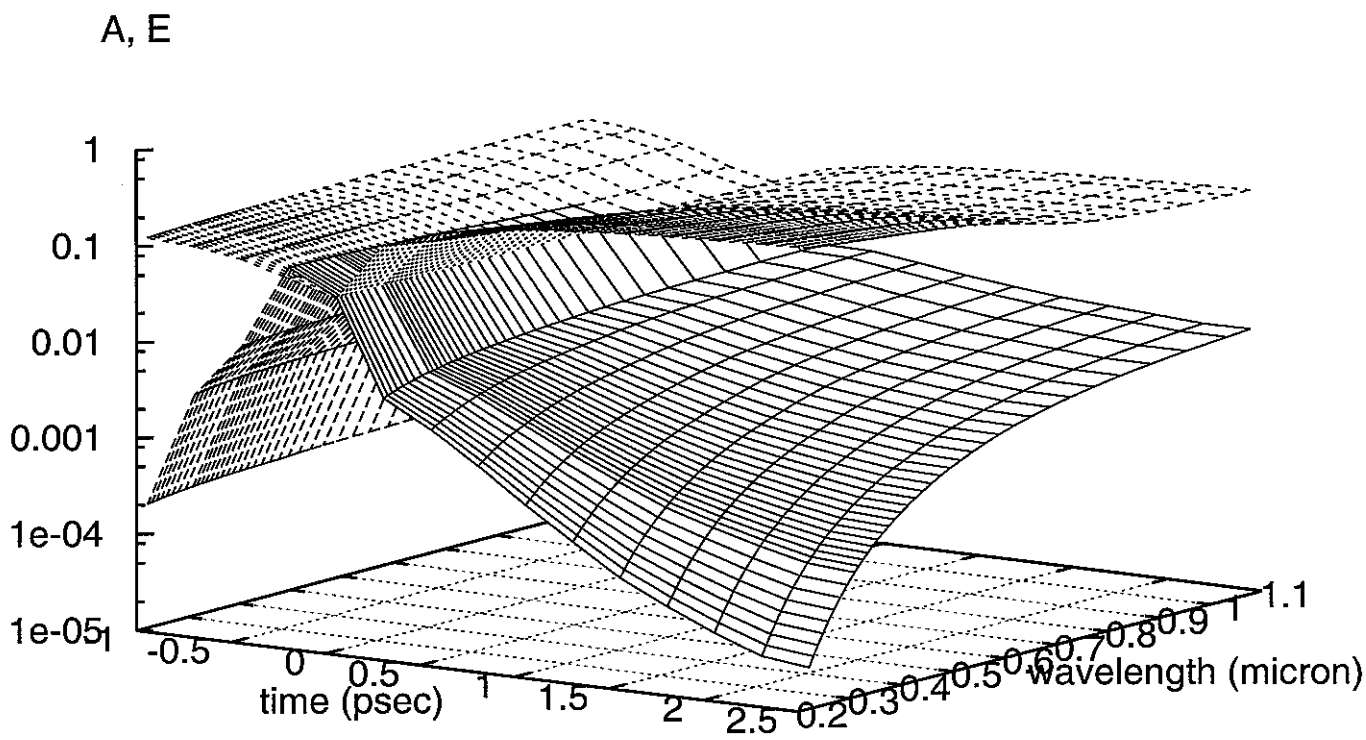
==> strong violation of Kirchhoff's law


Aluminum and Drude fit
10
1
0.1
0.01
n, k
0
0.2
0.4
0.6
0.8
1
Wavelength (microns)
plasma freq. = 15 eV
tau = 1.0 fsec

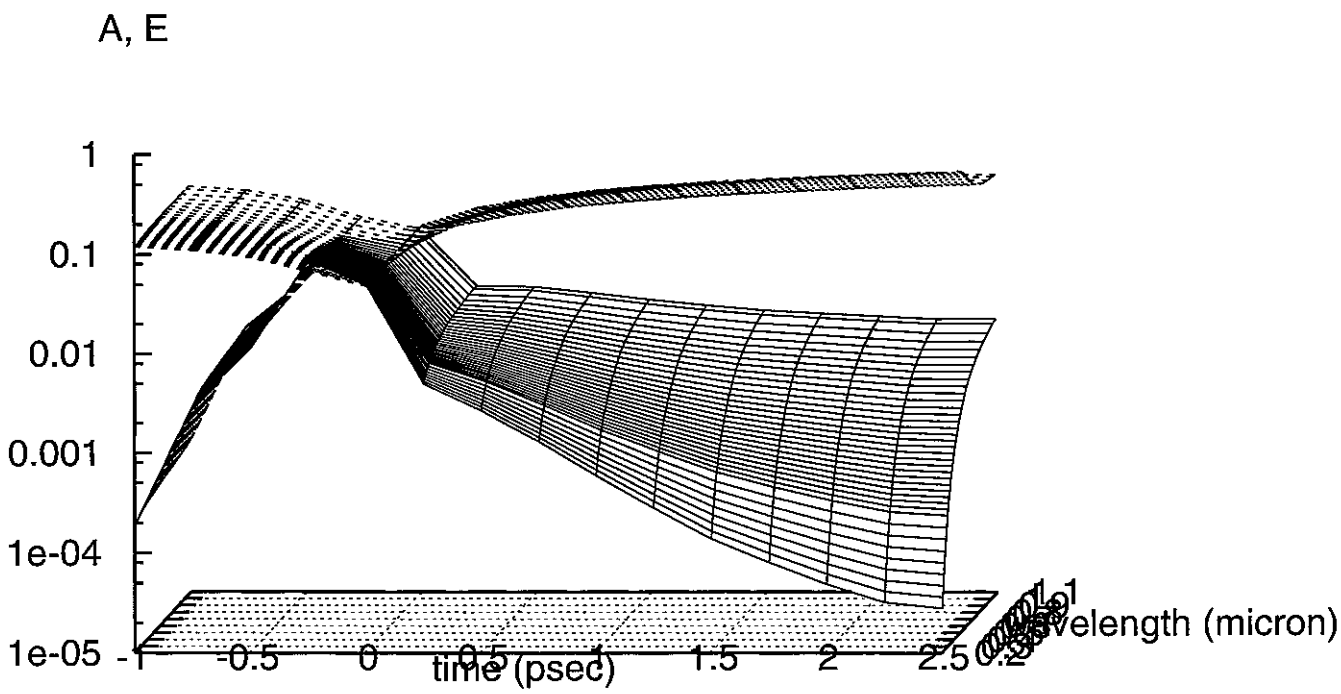
s,p Emission from Al 10 Mbar shock release



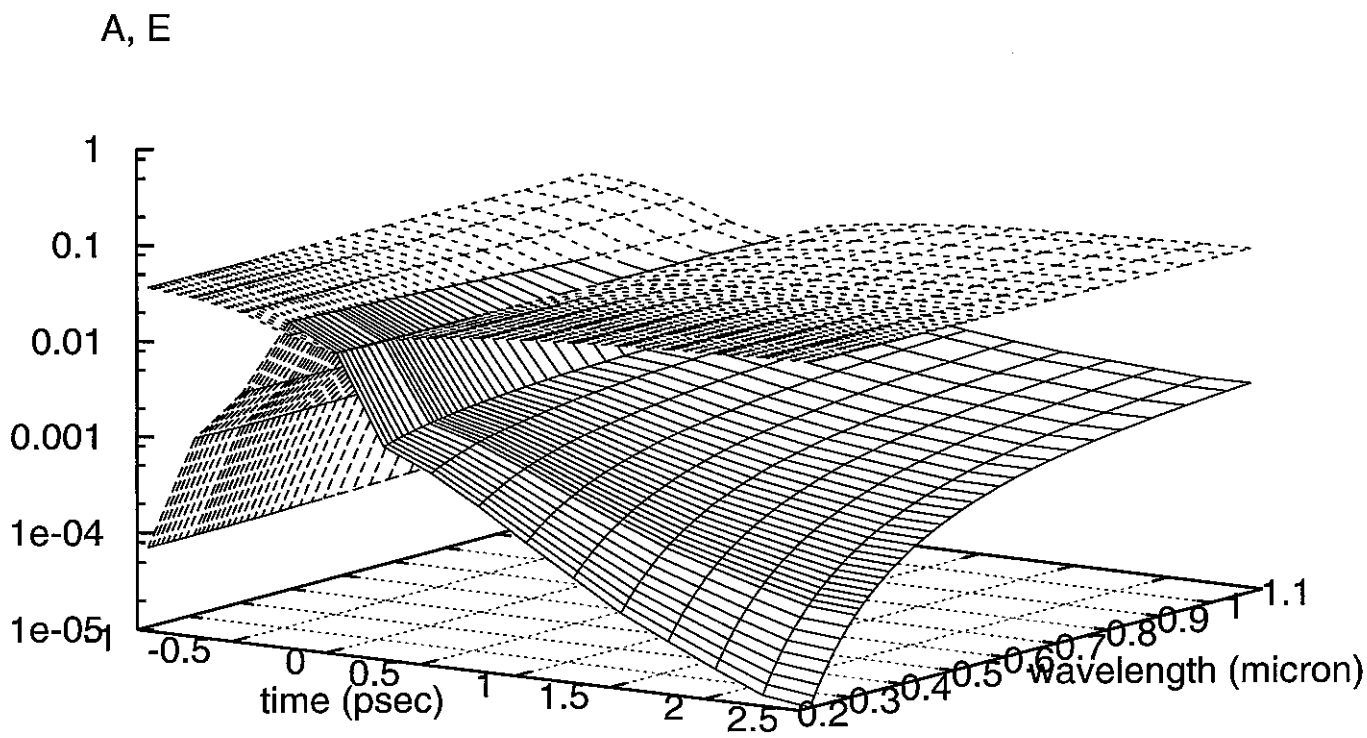
p-polarized E and A coefficients (Al shock release)



p-polarized E and A coefficients (Al shock release)



s-polarized E and A coefficients (Al shock release)



Difficulties and hopes

If light emission could be used to determine the shock temperature, that would be an advance for EOS science.

Difficulty: *Enough photons to get small error bars?*

Difficulty: *Fast enough detectors?*

Difficulty: *Is the emerging shock accurately parallel to the surface?*

Do small surface defects show up as early emission?

Deliberate tilt of the shock front to trade-off space and time resolution?
Is emission theory accurate enough to interpret <u>time-integrated</u> data?

Measure 2 θ's, 2 λ's, and 2 polarizations to constrain EOS models.

Summary and Conclusions

We describe a general theory of emission of radiation by hot dense matter.

Our computer code predicts light emission using material descriptions to be obtained from hydrodynamic codes.

Strong angle-dependent **polarization** of emitted light
Tested in recent experiments in LBNL, Tokyo (UEC) and NIFS (Toki);
Electrically-heated, laser-heated, e-beam heated metals

How rapidly does the polarization effect disappear with
Temperature gradients in the near-surface region?
Surface roughness or nonuniform expansion?

Polarization gives a new tool for improving the interpretation of pyrometry measurements of emission and may lead to a more convincing measurement of WDM plasma temperatures from pyrometry measurements.